

## EVALUATING THE READINESS FOR ROBOTICS AND AUTOMATION ADOPTION IN CONSTRUCTION MANAGEMENT: EVIDENCE FROM PAKISTAN

Hafiz Mughal<sup>1</sup>, Abdullah Mughal<sup>2</sup>

<sup>1</sup>MSc Construction Engineering and Management / BSc Industrial and Systems Engineering

<sup>2</sup>MSc Control Instrumentation and Engineering / BSc Control Engineering

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Corresponding Author: \*

Hafiz Mughal

### Abstract

Robotics and automation are increasingly being explored by the construction industry to improve productivity, safety, and project performance. However, significant variation is found in adoption levels across regions, particularly in developing countries. The current state of robotics and automation adoption in construction management in Pakistan is investigated by this study, and the industry's readiness for widespread implementation is evaluated. A quantitative, cross-sectional survey was conducted among construction professionals across Pakistan, yielding 118 valid responses. Constructs identified in the literature were used to develop the questionnaire, including current adoption level, application areas, perceived benefits, barriers to adoption, organizational readiness, and future adoption intention. Descriptive statistical analysis revealed that the adoption of robotics and automation in Pakistan remains limited, with most organizations confined to pilot or non-adoption stages. While respondents demonstrated moderate agreement regarding the potential benefits of automation, high initial investment cost, lack of skilled workforce, and limited technical support emerged as the most significant barriers. Correlation and regression analyses indicated that organizational readiness has a strong and positive influence on adoption level and future adoption intention. However, overall readiness was found to be insufficient to support large-scale implementation. The findings suggest that comprehensive adoption of robotics and automation is not yet fully prepared for by Pakistan's construction industry. Targeted interventions focusing on workforce development, organizational capacity building, and supportive policy frameworks are required to accelerate digital transformation. Empirical evidence from a developing country context is contributed by this study and practical insights for industry practitioners and policymakers seeking to advance Construction Industry 4.0 are offered.

### INTRODUCTION

The construction industry plays a vital role in national economic development and infrastructure delivery (1); however, it has

traditionally been characterized by low productivity growth, high safety risks (2), and

slow technological advancement (3). In recent years, robotics and automation have emerged as key components of Construction Industry 4.0 (4-6), offering opportunities to enhance efficiency, safety, quality, and decision-making in construction management (7-10). Technologies such as autonomous equipment, robotic systems, drones, and AI-enabled monitoring tools are increasingly being explored across global construction markets (11-15).

In developed economies, the adoption of robotics and automation has progressed beyond experimental use toward more systematic implementation, driven by labor shortages, safety regulations, and productivity demands (16-18). In contrast, developing countries continue to experience slower adoption due to financial constraints, limited technological infrastructure, shortage of skilled workforce, and reliance on labor-intensive practices (20-24). This disparity underscores the importance of examining contextual and organizational factors that influence technology adoption in construction (25-27).

Pakistan's construction industry presents a particularly relevant context for such investigation. The sector contributes significantly to employment and economic growth, yet it remains largely labor-driven with limited digital integration (28). Although awareness of advanced construction technologies is gradually increasing, practical adoption of robotics and automation remains minimal (29). The extent to which construction organizations in Pakistan are prepared for large-scale adoption of these technologies remains largely unexplored (30).

Existing studies on robotics and automation in construction have predominantly focused on developed economies or have provided conceptual discussions without empirical validation (31). Empirical, survey-based evidence from developing countries—particularly Pakistan—remains limited. Moreover, few studies have quantitatively examined the combined influence of perceived benefits, barriers, organizational readiness, and future adoption intention within a single analytical framework (32-34).

### Research Objectives

To address these gaps, this study aims to evaluate the current state of robotics and automation adoption in construction management in Pakistan. The specific objectives of the study are to:

**Assess the current level of adoption** of robotics and automation in construction management practices in Pakistan.

**Identify key application areas** where robotics and automation are currently used or considered feasible.

**Examine perceived benefits** associated with the adoption of robotics and automation in construction projects.

**Analyze the major barriers** hindering the adoption of robotics and automation in the Pakistani construction industry.

**Evaluate organizational readiness** for robotics and automation adoption.

**Investigate the relationship** between organizational readiness, adoption level, and future adoption intention.

### Literature Review

The adoption of automation and robotics has historically been lagged in by the construction industry, despite being a significant global economic sector, compared to other industries (36-38). However, the potential benefits of these technologies are being increasingly recognized to address persistent challenges such as labor shortages, low productivity, safety risks, and quality control issues (36, 37, 39-42). This literature review is structured around the key constructs used in the questionnaire, ensuring a direct link between theoretical foundations and empirical measurement. The review synthesizes existing research on robotics and automation in construction management to justify the selection of survey variables and support the development of the conceptual framework.

### Current Adoption of Robotics and Automation in Construction

The adoption of robotics and automation (R&A) in construction is still considered slow, with applications typically found in specific, often

controlled, environments (42,43). Early developments in Europe, dating back to the 1990s, were focused on areas such as concrete and asphalt mixing, precast concrete unit manufacturing, and masonry prefabrication (44). Ideal conditions for automation are provided by this trend towards prefabrication and off-site construction due to its more controlled manufacturing environment compared to dynamic on-site conditions (45,46).

Recent advancements, driven by increased computational power and breakthroughs in artificial intelligence (AI), have spurred more research and development in construction robotics (38,47). While the practical application rate for on-site construction remains limited, there is increasing interest in utilizing R&A for improving productivity and safety (48,49). The trend indicates a shift from purely automated systems to human-robot collaboration (HRC) to leverage both robot precision and human dexterity and problem-solving skills (50,51).

#### Application Areas of Robotics and Automation

Robotics and automation are being explored and implemented across various construction activities, aiming to enhance efficiency and safety. Robotics are widely used in controlled factory settings for the prefabrication of building components, such as precast concrete units and modular wall components, which are offered benefits in energy reduction, waste minimization, and shorter construction times (45,52,53). Many challenges associated with on-site deployment are mitigated by this off-site approach (54,55).

While challenging, repetitive and hazardous on-site tasks are increasingly being performed by robots. Examples include automated bricklaying systems, such as the BRIX prototype which can construct brick walls autonomously (56). Other applications include structural assembly, façade installation, welding, painting, and demolition (47, 49). Tasks like material transport and infrastructure inspection are also being developed for autonomous mobile robots (57).

Computer vision techniques are being investigated for the automated recognition and monitoring of construction equipment, reducing

the manual effort of data collection and annotation (58).

Building Information Modeling (BIM) is being integrated with mixed reality for remote interactive collaboration in facilities management, enhancing inspection and maintenance tasks (59). Research includes dynamics of grouping characteristics for shield tunneling machine thrust systems to improve performance (60). BIM-based information systems are being developed for the end-of-life disposal of construction and demolition waste, supporting eco-friendly practices based on the 3R (Reduce, Reuse, Recycle) principle (61). An emerging area where the strengths of both humans and robots are combined. This is particularly relevant in timber prefabrication, where flexibility and productivity can be increased by HRC (51, 62). The tasks involved in HRC range from cutting and milling to assembling and lifting, with humans acting as supervisors and cooperators, providing cognitive skills, while physical capabilities and precision are offered by robots (62). Blockchain and intelligent contracts are emerging as innovations to streamline contractual processes in construction (63).

#### Perceived Benefits of Robotics and Automation

The perceived benefits of adopting R&A in construction are multifaceted and many long-standing industry issues are addressed. Productivity can be significantly boosted by automation through the automation of repetitive tasks, reduction of manual labor, and acceleration of project timelines (39,41,64). Notable gains in this area are offered by off-site construction with automation (45 52). Hazardous tasks can be performed by robotics, thereby reducing the risk of accidents and injuries for human workers, leading to safer working conditions (39, 50, 41, 65,43,66).

Robots can execute tasks with higher accuracy and consistency than human workers, leading to higher-quality construction and fewer errors (39, 66, 50). For instance, high-quality output can be ensured by automated systems in precast concrete production (52). While initial investment can be high, reduced labor costs, waste minimization,

and optimized resource utilization are included in the long-term benefits, potentially leading to overall cost savings (39,67,53).

With increasing challenges in attracting and retaining skilled labor, a solution is offered by robots to fill workforce gaps and supplement human capabilities (40, 41, 68, 66, 52).

Sustainability: Sustainable construction practices can be contributed to by R&A through efficient material use, waste reduction, and optimized energy consumption (45, 53). Econo-enviro-friendly disposal of construction and demolition waste can be aided by BIM-based systems, for example (61). Greater design freedom and customization are allowed by advanced robotics, enabling complex architectural designs that might be difficult or impossible with traditional methods (50, 57).

### Barriers to Adoption of Robotics and Automation

Despite the numerous benefits, significant barriers to the widespread adoption of R&A are faced by the construction industry. The substantial capital investment required for purchasing and implementing robotic systems is a primary deterrent for many construction companies, particularly those with tight profit margins (39, 42, 47, 46).

There is a significant shortage of professionals with the necessary skills to operate, program, and maintain advanced robotic systems, creating a gap between technology availability and effective implementation (40, 68, 69, 52). The fragmented nature of the construction industry, with unique project demands and temporary project organizations, makes it challenging to standardize processes and integrate robotic solutions effectively (40,65,46).

Cultural resistance to new technologies, coupled with a lack of awareness about the capabilities and benefits of robotics, hinders adoption (42,69). Successful deployment is crucially impacted by stakeholders' perception and acceptance (70,71). Unlike controlled factory settings, construction sites are often unstructured, dynamic, and unpredictable, posing significant challenges for

robot navigation, safety, and task execution (41, 50, 56).

Current robotic technologies may still have limitations in terms of dexterity, adaptability to varied tasks, and robustness in harsh construction environments (41, 50). The complexity of integrating various technologies (AI, IoT, robotics) can also be a hurdle (38). The absence of clear industry standards, guidelines, and regulatory frameworks for the use of robots in construction creates uncertainty and reluctance among practitioners (65, 67). Low profit margins, fluctuating demand, and perceived high risks in the construction industry contribute to a conservative approach toward investing in new technologies (65,46).

### Organizational Readiness for Automation Adoption

Organizational readiness for automation adoption is a critical determinant of successful implementation (37). Several factors like strong leadership commitment and a clear strategic vision for integrating R&A are essential to drive investment and overcome internal resistance (72,73). Adequate financial backing is necessary to cover the high initial costs of robotic systems, as well as ongoing maintenance, training, and integration expenses (40,42). Training of the existing workforce or hiring of new talent with expertise in robotics, AI, and related technologies must be invested in by organizations (40,68). This includes engineers, programmers, and technicians capable of deploying and managing these systems. An organizational culture that embraces innovation, is willing to adapt existing processes, and understands the long-term benefits of technology adoption is crucial (70,74). Developing partnerships with technology providers, research institutions, and other industry stakeholders can facilitate knowledge transfer, access to specialized expertise, and shared development costs (75).

Organizations need robust frameworks to assess and mitigate the risks associated with new technology adoption, including technical failures, project delays, and data security concerns (67,72).

### Future Intention to Adopt Robotics and Automation

The future intention to adopt robotics and automation in construction is strong, driven by the compelling need to address current industry challenges and capitalize on technological advancements (37,39). This future trajectory is being influenced by several factors like continuous advancements in AI, machine learning, sensor technology, and mechatronics that are making robots more capable, adaptable, and cost-effective (38,40,47,50). Promising, yet underexplored, paradigms like reinforcement learning and imitation learning could enhance robot capabilities in unstructured environments (41). The ongoing demand for higher productivity, improved efficiency, and faster project delivery will continue to push the industry towards automation (37,74). Greater reliance on automation will be necessitated by persistent labor shortages and an aging workforce to maintain operational capacity (40,68). The adoption of technologies that reduce waste, optimize material use, and minimize environmental impact will be driven by the increasing focus on environmental sustainability (45,53). The use of robots for hazardous tasks will continue to be motivated by the inherent dangers of construction work, prioritizing worker safety (39,65). As the benefits of R&A are demonstrated by some companies, competitive pressures will encourage others to be followed to maintain their market position

(39). Supportive government policies, funding for research and development, and the establishment of regulatory frameworks can accelerate adoption (67,76).

### Summary and Research Gap

Transformative potential for the construction industry is offered by robotics and automation, with improvements in safety, productivity, quality, and sustainability promised (39,42,66). Current applications are ranged from highly controlled off-site prefabrication to emerging on-site robotic systems and human-robot collaboration (45,51,56). However, significant barriers— including high costs, a lack of skilled

personnel, industry fragmentation, and the unstructured nature of construction sites—are continued to be impeded by these (40,42,65).

### Organizational

readiness, encompassing leadership, financial investment, technical expertise, and a culture open to innovation, is considered crucial for overcoming these hurdles (72). A positive future intention for adoption is maintained, fueled by technological advancements and the urgent need to address industry challenges (37,38). Despite the growing body of literature, several research gaps are persisted, like the need for more empirical research to quantitatively assess the long-term economic, social, and environmental impacts of R&A adoption in diverse construction contexts

(53). Further research is required on effective strategies for integrating complex robotic systems with existing construction workflows, project management practices, and other digital technologies like BIM (59,75). Comprehensive studies are needed to understand the exact workforce implications of increasing automation, including job displacement, new skill requirements, and the development of effective training and educational models (68). While HRC is a promising area, deeper exploration into optimizing human-robot interfaces, communication protocols, and task allocation is needed to maximize efficiency and safety in collaborative environments (51,62). A critical need for the development of robust industry standards, guidelines, and regulatory frameworks to facilitate the safe and effective deployment of construction robots exists (65,67). The development of decision support systems to assist organizations in evaluating the potential benefits and challenges of robotic equipment for specific construction processes is considered vital (77,71). Continued research and development are deemed essential to enhance the autonomy, perception, and navigation capabilities of robots to operate effectively in dynamic and unpredictable on-site construction environments (41).

## Research Methodology

### Research Design

This study employed a quantitative, cross-sectional survey research design to evaluate the current state of robotics and automation adoption in construction management in Pakistan. The design was selected to enable the measurement of adoption levels, perceived benefits, barriers, organizational readiness, and future adoption intention, and to statistically examine the relationships among these variables.

A quantitative approach was considered appropriate because the study aimed to generate empirical evidence supporting conclusions about industry readiness rather than exploratory or anecdotal insights.

### Development of Research Constructs and Questionnaire

The questionnaire was developed based on a structured review of the literature on construction robotics, automation, and Construction Industry 4.0. Key constructs repeatedly identified in prior studies—namely current adoption level, application areas, perceived benefits, barriers to adoption, organizational readiness, and future adoption intention—were operationalized into measurable survey items.

Each construct was measured using multiple closed-ended statements to enhance reliability and avoid subjective written responses. A five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) was used across all perceptual constructs, ensuring consistency and suitability for statistical analysis.

The final questionnaire structure directly reflects the analytical framework tested in the results section, particularly the relationships between barriers, organizational readiness, and adoption outcomes.

### Target Population and Data Collection

The target population comprised construction professionals actively involved in construction management in Pakistan, including project managers, site engineers, BIM professionals,

consultants, and senior management personnel. These respondents were selected due to their direct involvement in decision-making, planning, and implementation of construction technologies. Data were collected using an online questionnaire distributed through professional networks, industry contacts, and digital communication platforms commonly used by construction practitioners. Participation was voluntary, and confidentiality was assured to encourage accurate and unbiased responses.

A total of 118 valid responses were obtained and deemed sufficient for the descriptive and inferential statistical analyses conducted in this study.

### Measurement Reliability and Validity

To ensure measurement reliability, Cronbach's alpha was calculated for all multi-item constructs, including perceived benefits, barriers, organizational readiness, and future adoption intention. All constructs achieved alpha values exceeding the recommended threshold of 0.70, indicating acceptable internal consistency.

Content validity was established by grounding all questionnaire items in existing literature and aligning them with the study's conceptual framework. The consistency between the constructs, questionnaire items, and analytical results further supports the validity of the measurement instrument.

### Data Analysis Procedures

The collected data were analyzed using **statistical analysis software** following a structured, multi-stage procedure aligned with the study objectives: **Descriptive statistics** (frequencies, means, and standard deviations) were used to assess respondent characteristics, current adoption levels, and overall perceptions of robotics and automation.

**Mean ranking analysis** was applied to identify the most significant perceived benefits and barriers influencing adoption.

**Pearson correlation analysis** was conducted to examine the relationships between organizational readiness, perceived barriers, adoption level, and future adoption intention.

**Multiple regression analysis** was employed to identify significant predictors of robotics and automation adoption, with organizational readiness treated as a key explanatory variable.

These analytical techniques enabled the study to quantitatively demonstrate that, despite moderate awareness of benefits, organizational readiness remains insufficient, contributing to low adoption levels in the Pakistani construction industry.

constructs enabled the identification of moderate benefit perception, high barrier severity, and limited organizational readiness, which were confirmed through descriptive and inferential analyses. Furthermore, the regression results validated the central role of organizational readiness in explaining adoption outcomes, confirming the suitability of the research design and analytical strategy.

#### 4 Alignment of Methodology with Results

The methodological approach directly supports the study's findings. The use of Likert-scale

#### Results and Analysis

##### Respondent Profile

Category	Frequency	Percentage (%)
Job Role		
Project/Construction Manager	42	35.6
Site Engineer	39	33.1
BIM/Digital Engineer	17	14.4
<b>Senior Management</b>	20	16.9
Experience		
< 5 years	21	17.8
5 - 10 years	36	30.5
11 - 20 years	40	33.9
> 20 years		

Table 1: Respondent Demographic Profile (N = 118)

Reliability Analysis

Constructs	Number of items	Cornbach's Alpha
Adoption level	4	0.81
Application areas	7	0.83
Perceived benefits	6	0.87
Barriers	6	0.84
Organizational readiness	5	0.79
Future intention	3	0.82

Table 2: Reliability Analysis of Survey Constructs

All constructs exceed the 0.70 threshold, confirming internal consistency.

Adoption level analysis

Constructs	Number of items
No adoption	28.0
Real projects only	34.7
Used in some projects	21.2
Used in most projects	16.1

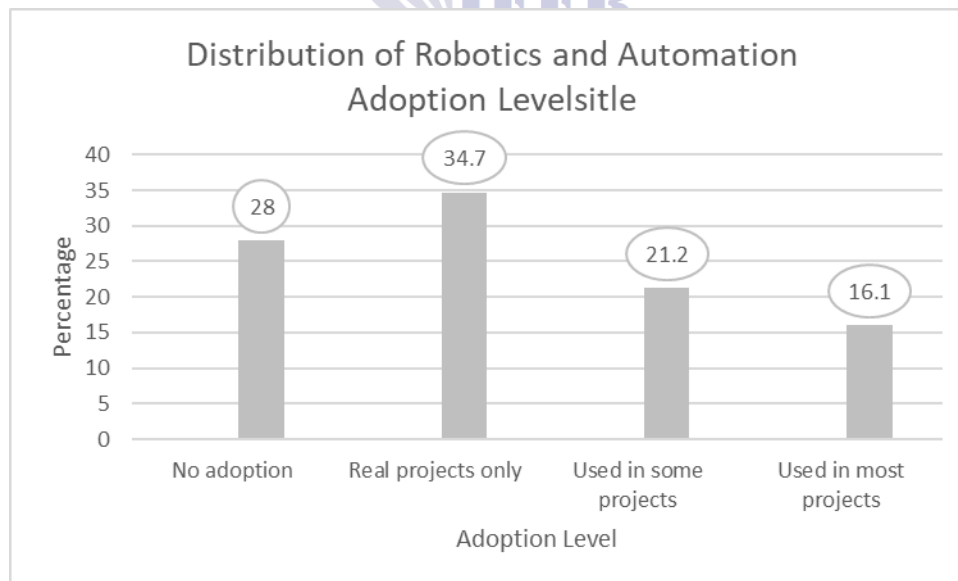


Figure 1: Distribution of Adoption Levels Application Areas

**Table 3: Level of Robotics and Automation Adoption**

Application Areas	Mean	Std. Dev.
Site surveying & inspection	3.72	0.91
Safety monitoring	3.58	0.88
Project planning & scheduling	3.44	0.95
Quality monitoring	3.21	0.92
Material handling	2.67	0.99
Structural construction	2.41	1.02
Earthworks	2.36	1.07

**Table 4: Mean Scores of Application Areas**

Automation is concentrated in non-core activities, while primary construction operations remain manual.

### 5.5 Perceived Benefits

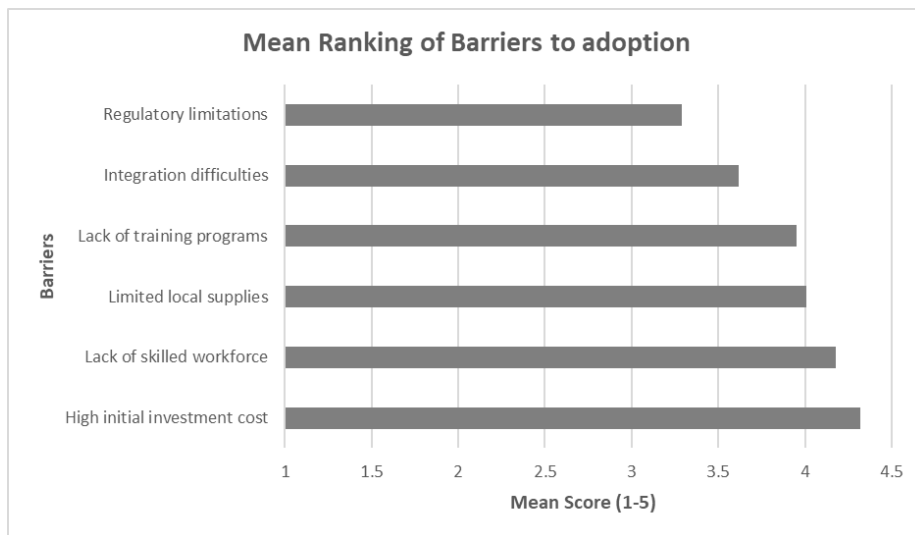
Benefit	Mean	Rank
Improved productivity	4.28	1
Enhanced site safety	4.19	2
Improved construction quality	4.05	3
Reduced project duration	3.98	4
Reduced labor dependency	3.87	5
Improved cost control	3.74	6

**Table 5: Perceived Benefits of Robotics and Automation**

High mean scores indicate strong positive perception, despite limited adoption.

**Barriers to Adoption**

Barrier	Mean	Rank
High initial investment cost	4.32	1
Lack of skilled workforce	4.18	2
Limited local supplies	4.01	3
Lack of training programs	3.95	4
Integration difficulties	3.62	5
Regulatory limitations	3.29	6



**Figure 2: Mean Ranking of Barriers**

Financial and capability constraints dominate, confirming low readiness.

**Table 6: Barriers to Robotics and Automation Adoption**

**Organizational Readiness**

Readiness Factor	Mean
Digital strategy	3.21
Management support	3.34

**Table 7: Organizational Readiness Assessment**

Employee training	2.89
BIM integration	3.02
External collaboration	2.76

Readiness remains moderate to low, especially in training and collaboration.

**Correlation analysis**

**Table 8: Pearson Correlation Matrix**

Variable	Adoption	Benefits	Barriers	Readiness
Adoption level	1			
Perceived Benefits	0.41*	1		
Barriers	-0.47**	-0.36**	1	
Organizational Readiness	0.58**	0.49**	-0.44**	1

Note: p < 0.01

Organizational readiness is the strongest positive driver of adoption.

**Regression Analysis**

**Table 9: Multiple Regression Results**

Predictor	$\beta$	t-value	Significance
Organizational readiness	0.46	5.82	p < 0.001
Barriers	-0.31	-4.17	p < 0.01
Perceived Benefits	0.12	1.41	Not significant

**Discussion**

This study set out to evaluate the current state of robotics and automation adoption in construction management in Pakistan using a quantitative survey-based approach. The findings clearly indicate that, despite growing awareness of automation technologies, the Pakistani construction industry is not yet fully prepared for large-scale adoption.

The limited adoption suggests that robotics and automation are currently perceived as experimental rather than strategic tools within construction management practices in Pakistan. This finding aligns with prior studies indicating that developing economies often face structural and institutional challenges that delay digital transformation in construction.

**Adoption Status and Industry Maturity**

The adoption level analysis (Table 3 and Figure 1) reveals that the majority of surveyed organizations remain at early stages of adoption, with over 60% reporting either no adoption or implementation limited to pilot projects. This reflects a low level of technological maturity, consistent with observations in other developing construction markets. While some firms have experimented with robotics and automation, widespread institutionalization across projects is still lacking.

**Application Areas of Robotics and Automation**

The analysis of application areas (Table 4) shows that robotics and automation are primarily utilized in supportive and non-core construction activities, such as site surveying, inspection, and safety monitoring. In contrast, core construction operations, including structural construction and earthworks, exhibit significantly lower adoption levels.

This trend suggests a risk-averse adoption behavior, where firms prioritize technologies with lower implementation complexity and minimal disruption to traditional workflows. Similar patterns have been observed in earlier research, which emphasizes that organizations often begin automation adoption in

peripheral tasks before extending it to core construction processes.

### Perceived Benefits versus Actual Adoption

Despite low adoption levels, respondents reported strong agreement regarding the potential benefits of robotics and automation (Table 5). High mean scores for improved productivity, enhanced safety, and better construction quality indicate that industry professionals recognize the value proposition of automation technologies.

However, the regression results (Table 9) demonstrate that perceived benefits alone do not significantly predict adoption. This finding highlights a benefit-implementation gap, where positive attitudes toward technology do not translate into actual deployment. This gap underscores the importance of addressing structural and organizational constraints rather than focusing solely on awareness-building initiatives.

### Barriers Hindering Adoption

The barrier analysis (Table 6 and Figure 2) identifies high initial investment costs and lack of skilled workforce as the most critical obstacles to adoption. These barriers reflect both financial and human capital constraints, which are particularly pronounced in developing construction markets.

The strong negative correlation between barriers and adoption level (Table 8) further confirms that these challenges substantially inhibit technological uptake. The dominance of cost-related barriers suggests that

many firms perceive robotics and automation as economically unviable under current market conditions, especially in a labor-intensive construction environment such as Pakistan.

### Organizational Readiness as a Key Enabler

Organizational readiness emerged as the strongest predictor of adoption in both correlation and regression analyses (Tables 8 and 9). Factors such as digital strategy, management support, employee training, and BIM integration exhibited moderate mean scores (Table 7), indicating partial but insufficient readiness.

This finding emphasizes that adoption is not merely a technological decision but a strategic organizational transformation. Firms lacking structured digital strategies and internal capabilities are unlikely to move beyond pilot implementations. The results reinforce the argument that readiness acts as a mediating mechanism between perceived benefits, barriers, and actual adoption outcomes.

### Implications for Pakistan's Construction Industry

Collectively, the findings suggest that Pakistan's construction industry is currently in a transitional phase, characterized by growing interest in automation but constrained by limited readiness and substantial barriers. The conceptual framework (Figure 3) effectively captures this dynamic by illustrating how barriers negatively influence organizational readiness, which in turn determines adoption level and future intentions.

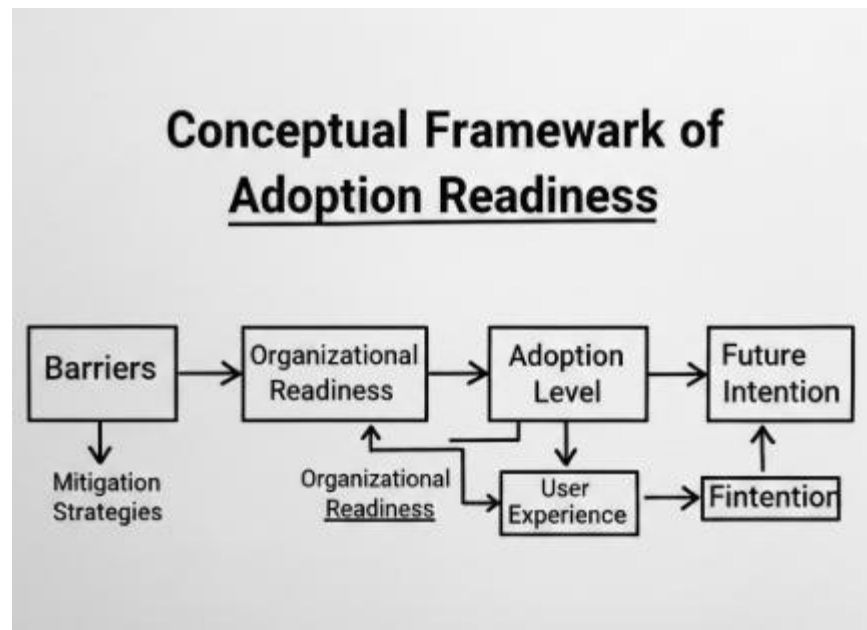


Figure 3: Conceptual framework of adoption readiness

Without targeted interventions aimed at capacity building, cost reduction, and skill development, the adoption of robotics and automation is likely to remain fragmented and slow. This has important implications for policymakers, industry leaders, and educational institutions seeking to promote Construction Industry 4.0 in Pakistan.

The findings confirm that Pakistan's construction industry is not yet fully ready for large-scale robotics and automation adoption. Although awareness and perceived benefits are high, economic constraints, limited skills, and insufficient organizational readiness hinder implementation. The results align with findings from other developing countries and reinforce the importance of institutional and capacity-building measures.

### Conclusions

Pakistan's construction industry is not yet fully ready for robotics and automation adoption due to low adoption levels (Table 3), dominant barriers (Table 6), and insufficient organizational readiness (Table 7).

### Recommendations

Based on the empirical findings of this study, several targeted recommendations are proposed to facilitate

the effective adoption of robotics and automation in construction management in Pakistan. These recommendations are grounded in the survey results and statistical analyses presented in Sections 5 and 6.

### Industry-Level Recommendations

The low level of adoption identified in Table 3 indicates that most construction organizations remain at pilot or non-adoption stages. To address this, construction firms should adopt a phased implementation strategy, beginning with automation in low-risk and high-impact areas such as site surveying, inspection, and safety monitoring, which already show relatively higher usage (Table 4). Gradual scaling can help organizations manage risk while building internal experience and confidence. Furthermore, firms should prioritize organizational readiness, which emerged as the strongest predictor of adoption (Table 9). This includes developing clear digital transformation strategies, strengthening BIM integration, and allocating dedicated budgets for technology experimentation and innovation.

### Workforce Development and Training

The lack of skilled workforce and insufficient training programs were ranked among the most critical barriers to adoption (Table 6 and Figure 2).

Construction organizations should therefore invest in structured training and upskilling programs focused on robotics, automation tools, and digital construction management systems.

Collaboration with universities, technical institutes, and professional bodies is recommended to ensure that curricula align with emerging Construction Industry 4.0 requirements. Enhancing workforce competence will directly improve organizational readiness, which has been shown to significantly influence adoption levels (Table 8).

### Policy and Government-Level Recommendations

High initial investment cost was identified as the most significant barrier to adoption (Table 6). To mitigate this challenge, policymakers should introduce financial incentives, such as tax relief, subsidized loans, or pilot project grants, to encourage firms to invest in robotics and automation technologies.

In addition, regulatory frameworks should be updated to support digital and automated construction practices. Clear standards and guidelines related to automation, robotics, and data integration would reduce uncertainty and encourage wider industry participation.

### Technology Providers and Industry Collaboration

The limited availability of local suppliers and technical support (Table 6) highlights the need for stronger collaboration between construction firms and technology providers. Partnerships with international robotics vendors, local startups, and research institutions can help bridge technical gaps and facilitate knowledge transfer.

Industry-wide collaboration platforms, such as innovation hubs or demonstration projects, can further accelerate adoption by showcasing successful use cases and reducing perceived implementation risks.

### Strategic Focus on Organizational Readiness

Given the strong positive relationship between organizational readiness and adoption (Tables 8 and 9), construction firms should treat readiness as a strategic priority rather than a secondary consideration. Senior management commitment, cross-functional coordination, and continuous

evaluation of digital capabilities are essential for transitioning from pilot projects to full-scale implementation.

### Future Research Directions

While this study provides empirical insights into the current state of robotics and automation adoption in construction management in Pakistan, several avenues for future research emerge.

First, future studies may expand the geographical scope beyond Pakistan to conduct comparative analyses between developing and developed countries. Such cross-country studies would help identify contextual differences in adoption drivers, policy support, and organizational readiness, thereby enriching the global understanding of Construction Industry 4.0 implementation.

Second, this research relied on a quantitative survey-based approach, which captures perceptions and self-reported practices. Future research could adopt mixed-method or qualitative approaches, such as case studies, interviews, or longitudinal investigations, to gain deeper insights into organizational decision-making processes, implementation challenges, and post-adoption performance outcomes.

Third, future studies may explore additional explanatory variables not covered in this research, such as organizational culture, leadership style, supply chain digitalization, and cybersecurity concerns. Incorporating these variables could improve the explanatory power of adoption models and provide a more holistic understanding of technology readiness.

Fourth, as robotics and automation technologies evolve rapidly, future research should examine the long-term impacts of adoption on project performance indicators, including cost efficiency, safety outcomes, workforce transformation, and sustainability performance. Longitudinal studies would be particularly valuable in assessing how adoption maturity develops over time.

Finally, future research may focus on the role of education and policy interventions, evaluating how government incentives, regulatory reforms, and construction education curricula influence organizational readiness and adoption behavior. Such studies would offer actionable insights for

policymakers and academic institutions seeking to accelerate digital transformation in the construction sector.

### Limitations

Despite providing valuable insights into the adoption of robotics and automation in construction management in Pakistan, this study has several limitations that should be acknowledged.

First, the study is based on a cross-sectional survey design, which captures respondents' perceptions at a single point in time. As a result, the findings may not fully reflect changes in adoption behavior or organizational readiness as technologies evolve. Longitudinal studies would be beneficial to examine how adoption patterns develop over time.

Second, the data were collected using self-reported responses, which may be subject to respondent bias, including overestimation or underestimation of adoption levels and organizational readiness. Although reliability analysis confirmed acceptable internal consistency of the survey constructs, future studies could strengthen validity by incorporating objective performance data or direct observations.

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- Third, the study focuses exclusively on the Pakistani construction industry, which limits the generalizability of the findings to other national contexts. Differences in economic conditions, regulatory frameworks, labor markets, and technological infrastructure may influence adoption outcomes in other countries. Therefore, caution should be exercised when extrapolating the results beyond Pakistan.
- Fourth, while this research examined key factors such as perceived benefits, barriers, and organizational readiness, other potentially influential variables—such as organizational culture, leadership orientation, supply chain integration, and cybersecurity concerns—were not included in the analysis. Including these factors in future research may provide a more comprehensive understanding of robotics and automation adoption.
- Finally, the sample size, although adequate for the statistical analyses performed, may not fully represent all segments of the construction industry, particularly small and informal firms that constitute a significant portion of the sector in Pakistan. Expanding the sample size and diversity of respondents could enhance the robustness of future studies.
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